A THERMODYNAMIC ANALYSIS OF AIR-CYCLE REFRIGERATION APPLIED TO COMFORT COOLING

A THESIS

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By

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SUMMARY

The objectives of this analysis were to obtain the coefficient of performance and horsepower per ton of refrigeration values for an air-cycle refrigeration system designed for comfort cooling under various operating conditions, to investigate various methods of increasing the coefficient of performance and thus decreasing the horsepower required per ton of refrigeration, and to make a brief thermodynamic comparison between air-cycle refrigeration and vapor-compression refrigeration systems under similar operating conditions.

An open air-cycle refrigeration system in which the area was conditioned for human occupancy was analyzed. The refrigerant was a mixture of dry air and water vapor. The entropy and enthalpy of a mixture of dry air and water vapor at various temperatures, pressures, and specific humidities were calculated. From these calculated mixture properties, the dry bulb temperature of the mixture versus the entropy of the mixture was plotted. Various cycles were represented on this figure and the corresponding dry bulb temperatures at various states were determined. Tables were prepared of enthalpy of the mixture at different dry bulb temperatures and specific humidities. By use of the enthalpy of the mixture, the coefficient of performance and horsepower per ton of refrigeration were calculated.

The theoretical coefficient of performance values of the air-cycle refrigeration system (values obtained from cycles assuming

isentropic compression and expansion) were better than the average value of vapor-compression systems in a standard vapor cycle. The actual coefficient of performance values of the air-cycle refrigeration system (values obtained from cycles assuming efficiencies of compression and expansion less than 100 per cent) were lower than the average value of vapor-compression systems in a standard vapor cycle. There exists an efficiency, around 95 per cent, where all of the coefficients of performance are identical, no matter what the temperature of the mixture entering the room is.

Two-stage compression and/or an increase in the temperature of the mixture entering the expander increases the coefficient of performance of the air-cycle refrigeration system. Better coefficients of performance are obtained for an air-cycle refrigeration system employing all room air instead of room air mixed with outside air as the refrigerant.

Increasing the back pressure of the expander decreases the coefficient of performance of the air-cycle refrigeration system.

If further analysis is made of an air-cycle refrigeration system it is recommended that this analysis be made as an actual operating analysis, which would include initial and operating costs. Similar values for a vapor-compression system could be obtained and an operating comparison could be made between the two systems.

CHAPTER I

INTRODUCTION

Objectives.--The objectives of this analysis are to obtain the coefficient of performance and horsepower per ton of refrigeration values for an air[1]-cycle refrigeration system designed for comfort cooling under various operating conditions, to investigate various methods of increasing the coefficient of performance and thus decreasing the horsepower required per ton of refrigeration, and to make a brief thermodynamic comparison between air-cycle refrigeration and vapor-compression refrigeration systems under similar operating conditions.

Background.--Air-cycle refrigeration was one of the earliest forms of cooling. The invention of air-cycle refrigeration, or the cold-air machine as it was originally called, is credited to Dr. Gorrie, who is said to have invented the first machine of this class in 1849 (1)[2]. The historical background of air-cycle refrigeration, together with excellent discussions on the advantages and disadvantages of the first cold-air machines and actual operating data on some of these machines are given by A. Wallis-Tayler (2), T. Lightfoot (3), and J. Coleman (4).

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[1] The term air is used to denote the usual mixture of gases which constitute the atmosphere, including water vapor.

[2] Numbers in parentheses refer to references in the "Literature Cited" section of the bibliography.

The air-cycle refrigeration system became obsolete for many years, but a new field of air conditioning developed in which the advantages of air as a refrigerant were apparent. This new field, in which air-cycle refrigeration equipment is now used almost exclusively, is the air conditioning of aircraft. R. Jordan and G. Priester (5), B. Messinger (6), and P. Scofield (7) discuss the application of air-cycle refrigeration to aircraft conditioning.

Review of the literature pertinent to air-cycle refrigeration did not yield any information on work that had previously been done on the thermodynamic analysis of an air-cycle refrigeration system applied to comfort cooling where the refrigerant is a mixture of dry air[3] and water vapor. Limited information is available for air-cycle refrigeration where the water vapor is neglected and the refrigerant is considered to be dry air. R. Hensley (8) constructed Mollier diagrams for air saturated with water vapor at low temperatures but the temperature range was not in the range for comfort cooling. This article by R. Hensley was very useful in comparing methods of calculation to those employed in this analysis.

Principle of Operation and Description of Cycle.--The principle of operation of the air-cycle refrigeration system is that during compression of the system the temperature increases (the system being the mixture of dry air and water vapor) and during its subsequent expansion the

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[3]The term dry air is used to denote the usual mixture of gases which constitute the atmosphere, exclusive of water vapor.

temperature of the system decreases. Figure 1 is a schematic diagram of an air-cycle refrigeration system where the work of expansion aids the work of compression. In the figure the system is classified as open, meaning that the conditioned area is cooled directly by the air from the expander, circulated through the conditioned area, and then compressed to the cooler pressure. In the closed system the air refrigerant is contained within the piping or component parts of the system at all times. The numbers on Figure 1 indicate the various states of the air during the cycle. The numbers and their designation are: 1 - entering the compressor; 2 or 2' - entering the cooler; 3 or 3' - entering the expander; 4 - entering the conditioned area (room); and 5 - area (room) conditions.

Plan of Analysis.--An open air-cycle refrigeration system in which the area is conditioned for human occupancy will be analyzed. The refrigerant is a mixture of dry air and water vapor. The entropy and enthalpy of a mixture of dry air and water vapor at various temperatures, pressures, and specific humidities will be calculated. From these calculated mixture properties, the dry bulb temperature of the mixture versus the entropy of the mixture can be plotted. Various cycles can be represented on this figure and the corresponding dry bulb temperatures at various states can be determined. Tables will be prepared of enthalpy of the mixture at different dry bulb temperatures and specific humidities. By use of the enthalpy of the mixture, the coefficient of performance and horsepower per ton of refrigeration can be calculated. The

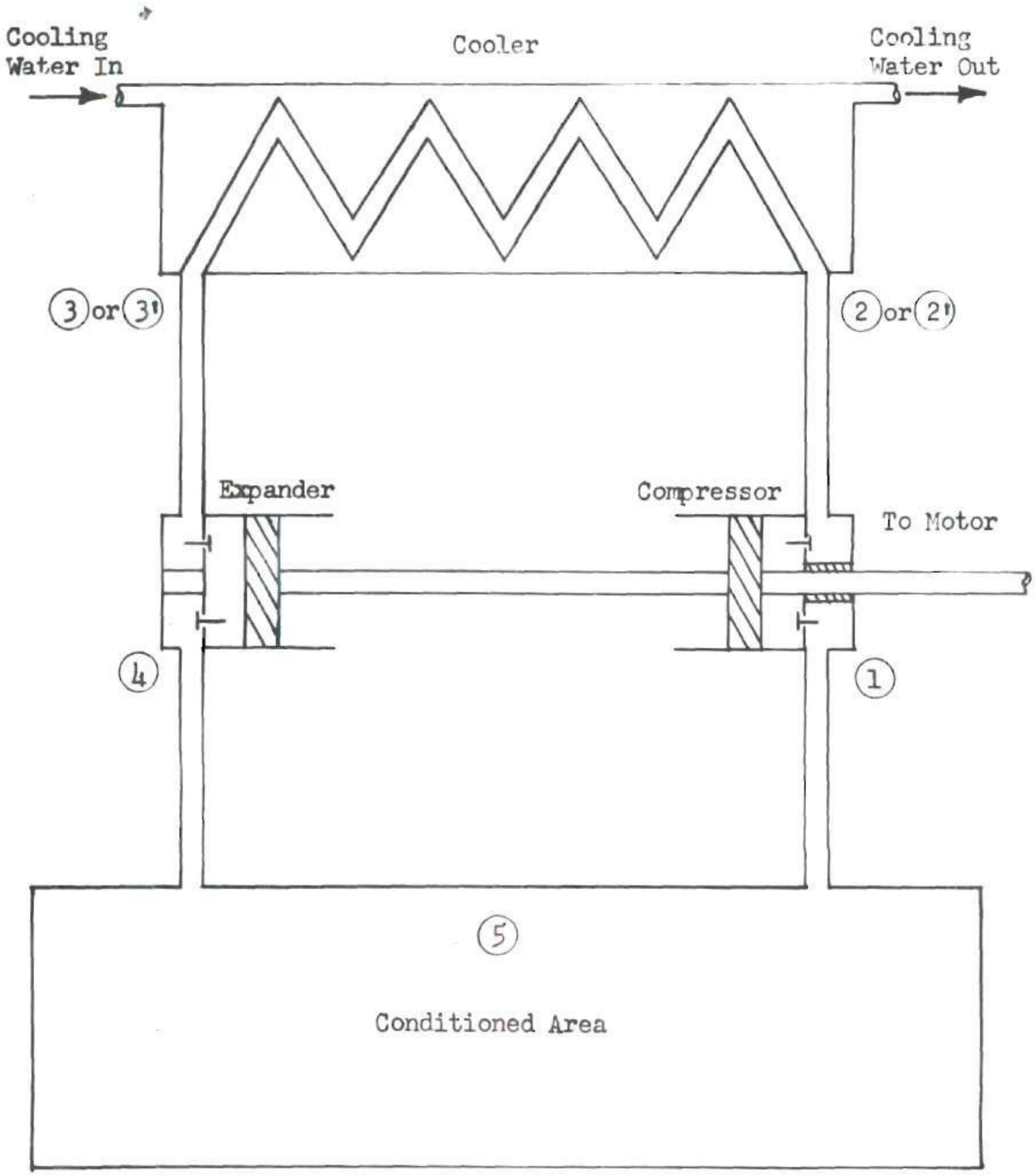


Figure 1. Schematic Diagram of an Open Air-Cycle Refrigeration System

coefficient of performance and horsepower per ton of refrigeration values will be compared with average values of vapor-compression systems in a standard vapor cycle (86 F condenser and 5 F evaporator temperatures). Various methods of increasing the coefficient of performance of the air-cycle refrigeration system will be investigated.

CHAPTER II

BASIC ASSUMPTIONS

Design Conditions.--The outside design dry bulb temperature and wet bulb temperature are 95 F and 76 F respectively, which are outside design conditions for Atlanta, Georgia (9). Conditioned area is maintained at 14.696 psia, 80 F dry bulb temperature, and a specific humidity, or moisture content, of 0.01097 lb water/lb dry air, which is approximately fifty per cent relative humidity (10). When some outside air is used for ventilation purposes the condition of the mixture entering the compressor, after mixing with room air, is 82 F dry bulb temperature and a specific humidity of 0.01148 lb water/lb dry air. The mixture entering the room is saturated between the temperature range of 50 F to 60 F.

Temperature of Mixture Entering Expander.--Cooling water for the cooler is available at 85 F and a 15 F temperature differential between the water and the mixture is allowed for good heat transfer. This assumption requires that the dry bulb temperature of the mixture leaving the cooler (entering the expander) must be equal to or greater than 100 F. This assumption is adhered to in the entire analysis except for the cases investigated where it is assumed that the mixture could be cooled to dry bulb temperatures lower than 100 F.

Gas Relations.--Calculation of the entropy and enthalpy of the mixture is based on the assumption that water vapor is a perfect gas and dry air is a semi-perfect gas over the temperature and pressure range considered. It is further assumed that the Gibbs-Dalton Law is valid over the range considered.

Reference States.--The reference pressure was chosen as one standard atmosphere, 14.696 psia. This choice of reference integrates the use of the data with some data on existing psychrometric charts. The values for the enthalpy and entropy of the mixture each depends upon two arbitrary constants which are determined when a state is chosen for each of the two components at which the property is zero. The entropy of dry air is zero at 0 F abs and 14.696 psia and the enthalpy of dry air is zero at 0 F abs, which are the constants in the Gas Tables (11). If the constants for water vapor are fixed by the Steam Tables (12), the properties of the water vapor may be taken from the Steam Tables without modification. The properties of the dry air and water vapor are zero at different states but as long as only differences between states are desired, the reference states need not be identical.

Enthalpy of Water Vapor.--The enthalpy of superheated water vapor equals the enthalpy of saturated water vapor at a given temperature. This assumption enables the values for the enthalpy of saturated vapor from the Steam Tables (13) to be used for the enthalpy of the water vapor. Referring to the Mollier diagram for steam in the Steam Tables (14), it is observed that the lines of constant temperature and constant enthalpy are nearly parallel at low pressures. This indicates that the enthalpy of the water vapor is a pure temperature function at low pressures, a conclusion which may also be shown employing the previous assumption that water vapor is a perfect gas over the temperature and pressure range considered (15). The maximum partial pressure of the water vapor in this analysis will be below 1 psia and therefore it is of negligible error to assume that the enthalpy of superheated water vapor equals the enthalpy of saturated water vapor at a given temperature.

Pressure Drop.--The pressure drops in the system due to friction are negligible. This assumption states that the pressure drop through the compressor valves, expander valves, cooler, and component piping is negligible. It does not assume that the pressure drop in the air distribution system is negligible. The air leaves the expander at room pressure and a fan must be employed to create sufficient pressure to overcome the pressure drop in the distribution system, except in the case investigated where the air leaves the expander at a pressure above room pressure.

CHAPTER III

PROCEDURE

Enthalpy and Entropy of Mixture.--The entropy of a mixture of dry air and water vapor at two specific humidities, 0.01097 lb water/lb dry air representing room conditions and 0.01148 lb water/lb dry air representing room air mixing with outside air, is calculated for pressures of 14.696 psia (room pressure), 15 psia, and 18 through 26 psia in increments of 1 psia within the temperature range concerned. The results are tabulated in Tables 2 through 12 in Appendix C. The entropy of a saturated mixture of dry air and water vapor at pressures of 14.696 psia and 15 psia is tabulated in Tables 13 and 14 in Appendix C. The enthalpy of the mixture of dry air and water vapor at the two specific humidities is tabulated in Table 15 in Appendix D. The enthalpy of a saturated mixture of dry air and water vapor at pressures of 14.696 psia and 15 psia is tabulated in Tables 16 and 17 in Appendix D. Methods of calculation and equations used are presented in Appendix B.

The entropy of the mixture in Btu/lb dry air deg F abs is plotted as the abscissa and the dry bulb temperature of the mixture in deg F is plotted as the ordinate in Figure 2 for pressures of 14.696 psia, 15 psia, and 18 through 26 psia and specific humidities of 0.01097 lb water/lb dry air and 0.01148 lb water/lb dry air. The cycles investigated are traced on Figure 2 and the dry bulb temperature at each state is obtained.

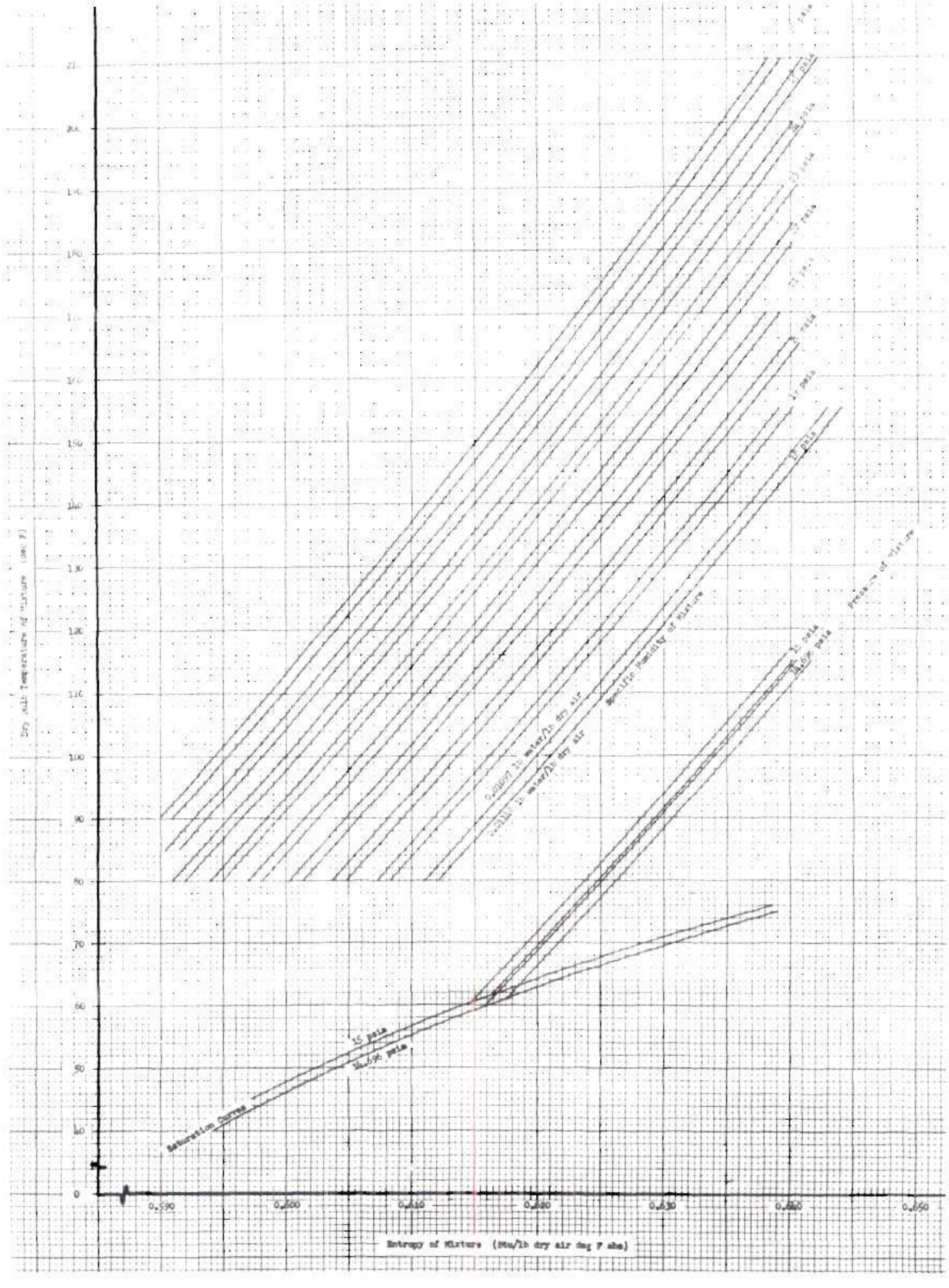


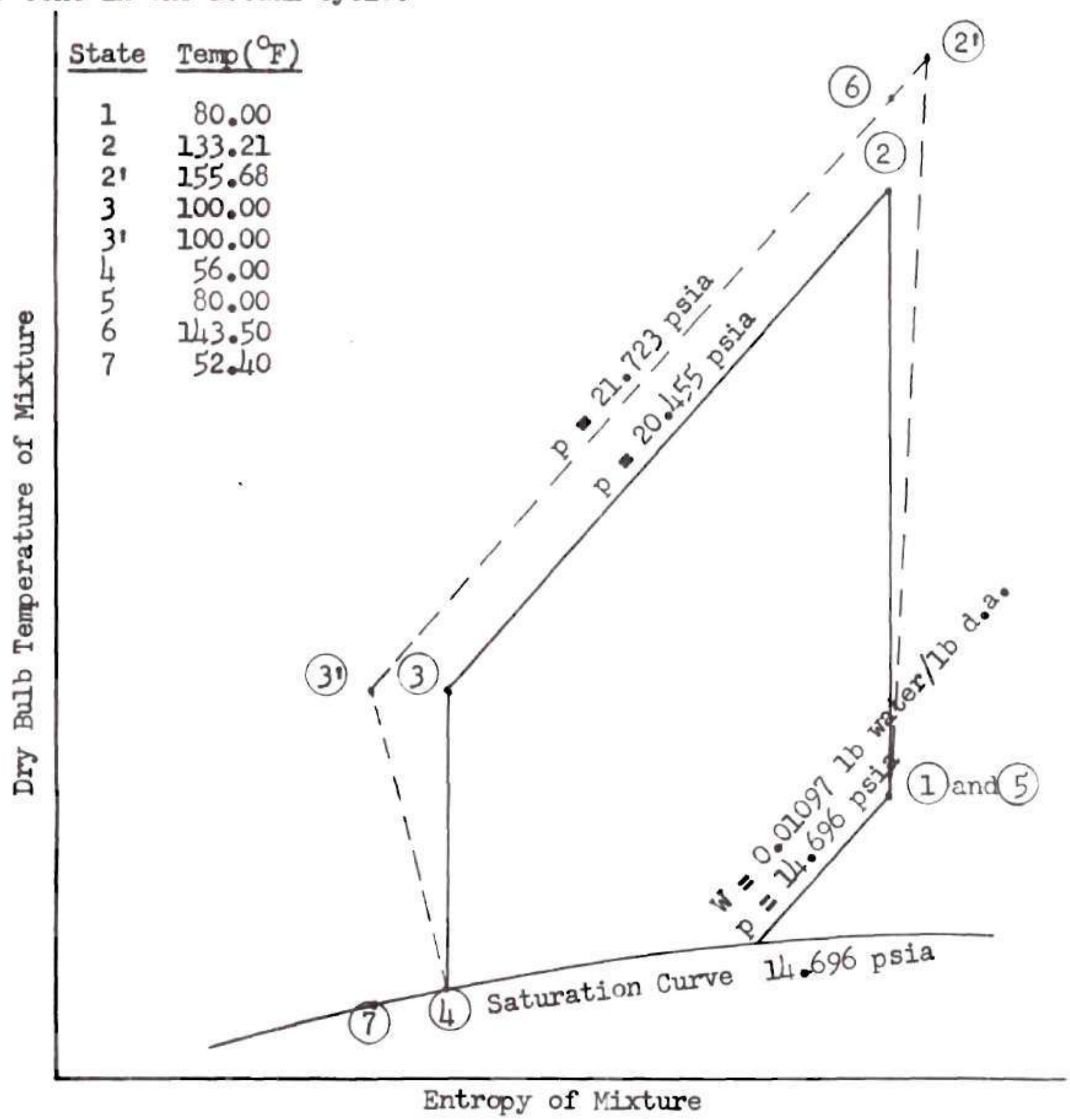
Figure 2. Dry Bulb Temperature of Mixture Versus Entropy of Mixture

The corresponding enthalpies are obtained from the tables in Appendix D.

Theoretical Cycle.--The theoretical cycle is defined as the cycle where isentropic compression and expansion are assumed, together with the assumptions in Chapter II. Reference will be made to Figures 3 and 4, which are tracings of the cycles on Figure 2, in the description of the cycle and location of states or points. The condition of the mixture entering the compressor is specified. This condition is at room pressure and either one of the two specific humidities. If all room air is to be recirculated, a specific humidity of 0.01097 lb water/lb dry air, designated by point 1 in Figure 3, is specified. Points 1 and 5 are analogous in Figure 3 because the mixture entering the compressor is room air. If room air is mixed with outside air for ventilation purposes, a specific humidity of 0.01148 lb water/lb dry air, designated by point 1 in Figure 4, is specified. Points 1 and 5 are different states in Figure 4 because the mixture entering the compressor is not the same as room air.

The condition of the mixture entering the conditioned area is specified, this point in the cycle being designated as point 4. Six conditions of the mixture entering the conditioned area are investigated, all saturated at dry bulb temperatures from 50 F to 60 F in increments of 2 degrees. From point 4 a line of constant entropy is drawn until it intersects a line of constant temperature of 100 F, designated by point 3. The specific humidity at this point corresponds to the specific humidity of the mixture entering the compressor. The pressure at this point is found by interpolating between the constant pressure lines of the same humidity

The following states and corresponding temperatures illustrate the states of a cycle where the temperature of the mixture entering the room is 56 F and the efficiency of compression and expansion is 85 per cent in the actual cycle.



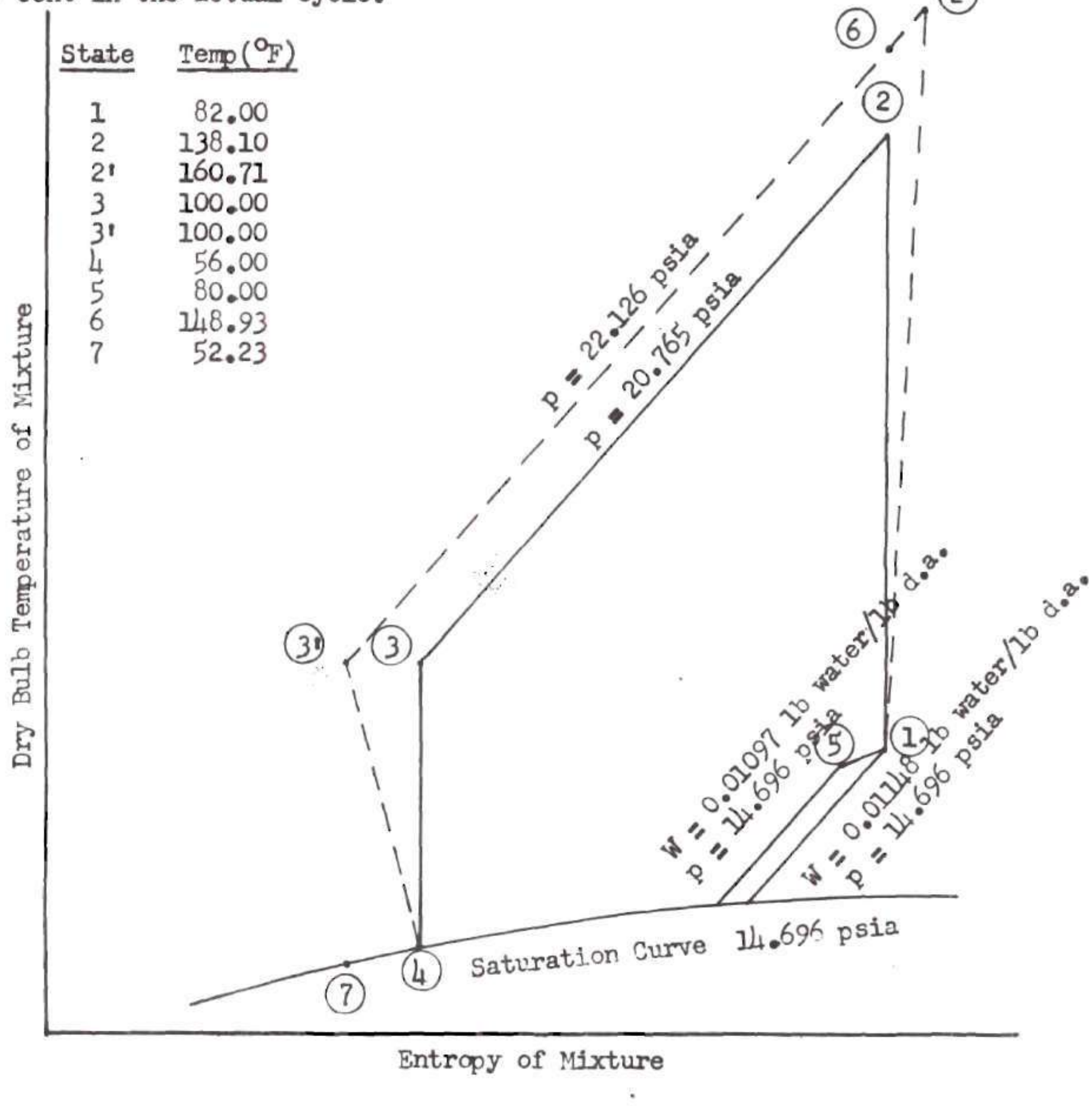
Notation:

Theoretical cycle
Actual cycle
Subscripts defined in text and Appendix A

Figure 3. Theoretical and Actual Air Refrigeration Cycles Employing All Room Air

The following states and corresponding temperatures illustrate the states of a cycle where the temperature of the mixture entering the room is 56 F and the efficiency of compression and expansion is 85 per cent in the actual cycle.

State	Temp(^{o}F)
1	82.00
2	138.10
2'	160.71
3	100.00
3'	100.00
4	56.00
5	80.00
6	148.93
7	52.23



Notation:

———	Theoretical cycle
- - -	Actual cycle
	Subscripts defined in text and Appendix A

Figure 4. Theoretical and Actual Air Refrigeration Cycles Employing a Mixture of Room Air and Outside Air

at 100 F. This pressure line is extended until it intersects a line corresponding to the entropy of the mixture entering the compressor. The point at which the constant pressure line, which corresponds to the pressure entering the expander, and the constant entropy line, which corresponds to the entropy of the mixture entering the compressor, intersect is designated as point 2. The temperatures at these various states are obtained from Figure 2 and the corresponding enthalpies are found by interpolation in the tables in Appendix D. By use of the enthalpies, the coefficient of performance and horsepower per ton of refrigeration are calculated and tabulated in Table 1 and Tables 18 through 22 for all room air and room air mixed with outside air. The methods of calculation are found in Appendix B.

Actual Cycle.--The actual cycle is defined as the cycle where efficiencies of compression and expansion are assumed, together with the assumptions in Chapter II. The efficiencies investigated are 80, 85, 90, and 95 per cent. Reference will again be made to Figures 3 and 4 in the description of the cycle and location of states or points. It is specified that the condition of the mixture entering the expander, point 3, must be at one of the two specific humidities and 100 F. It is further specified that the saturated temperature of the mixture entering the room, point 4, and the condition of the mixture entering the compressor, point 1, be identical with points 1 and 4 in the theoretical cycle. The enthalpy of the mixture at these points is found in the tables in Appendix D. Specifying points 3 and 4 fixes the actual work that the expander is capable of performing. The isentropic expansion that is necessary to give this actual work of expansion is calculated if the efficiency of the expander is known, as shown in Appendix B. By use of the isentropic work of expansion and the enthalpy of the mixture entering the expander, which is the enthalpy of the mixture at the specific humidity specified and 100 F, the enthalpy of a saturated mixture entering the room, assuming isentropic expansion, is calculated. The corresponding temperature is found by interpolating in the tables in Appendix D. This point is designated on Figures 3 and 4 as point 7.

A line of constant entropy is drawn through point 7 until it intersects a line of constant temperature of 100 F, designated as point 3'. The specific humidity at this point corresponds to the specific humidity of the mixture entering the compressor. The pressure at this point is found by interpolating between the constant pressure lines of the same humidity at 100 F. This pressure line is extended until it intersects a line corresponding to the entropy of the mixture entering the compressor. The point at which the constant pressure line, which corresponds to the pressure entering the expander, and the constant entropy line, which corresponds to the entropy of the mixture entering the compressor, intersect is designated as point 6. The temperature at this point is obtained and the corresponding enthalpy is found in the tables in Appendix D. By use of the isentropic work of compression and the efficiency of compression, the actual work of compression is calculated, as shown in Appendix B. The enthalpy and temperature of the mixture after compression, designated as point 2', is found utilizing the enthalpy of the mixture entering the compressor, point 1. The coefficient of performance and horsepower per ton of refrigeration are calculated and tabulated in Table 1 and Tables 18 through 22 for all room air and room air mixed with outside air. The methods of calculation are given in Appendix B.

Further Analysis.--A temperature entering the room of 56 F is specified and additional analyses are pursued. The coefficient of performance and horsepower per ton of refrigeration are calculated for isentropic compression and expansion, specifying temperatures of the mixture entering the expander of 95 F and 90 F. The same method of calculation for the theoretical cycle was followed. The results are tabulated in Table 18 in Appendix E.

The coefficient of performance and horsepower per ton of refrigeration are calculated for a two-stage compression cycle assuming isentropic compression and expansion. The mixture is compressed to 18 psia and cooled to 100 F in an intercooler in the first stage and compressed to the necessary pressure to give the required saturated temperature of the mixture entering the room and a temperature of 100 F entering the expander in the second stage. The results are tabulated in Table 23 in Appendix E.

The coefficient of performance and horsepower per ton of refrigeration are calculated assuming that the pressure leaving the expander is sufficient to overcome the pressure drop in the distribution system and thus eliminate the necessity of fans to create sufficient pressure to overcome this pressure drop. A pressure drop of 2 inches of water was assumed for the pressure drop in the distribution system, thus requiring that the pressure leaving the expander be 14.768 psia. Isentropic compression and expansion and a mixture temperature of 100 F entering the expander were assumed. Results are tabulated in Table 18 in Appendix E.

CHAPTER IV

DISCUSSION OF RESULTS

General.--The coefficient of performance and horsepower per ton of refrigeration values for an air-cycle refrigeration system operating under the assumptions made previously are tabulated in Table 1. Data for each of the cycles analyzed are given in Tables 18 through 23 in Appendix E. Table 18 also gives the coefficient of performance and horsepower per ton of refrigeration values for an air-cycle refrigeration system under conditions of operation that differ from the assumptions made. The assumptions for these cycles that differ from the basic assumptions are dry bulb temperatures of the mixture entering the expander of 95 F and 90 F instead of 100 F, and a pressure of the mixture entering the room of 14.768 psia instead of 14.696 psia. Table 23 in Appendix E gives the coefficient of performance and horsepower per ton of refrigeration values for a two-stage isentropic compression cycle with the temperature of the mixture entering the expander of 100 F.

Efficiency.--Reference is made to Table 1. For a given temperature of the mixture entering the room, as the efficiency of compression and expansion increases, the coefficient of performance increases and the horsepower per ton of refrigeration decreases. For isentropic compression and expansion, an efficiency of 100 per cent, as the temperature of the mixture entering the room increases, the coefficient of performance increases.

Table 1. Coefficient of Performance and Horsepower per Ton of Refrigeration for an Air-Cycle Refrigeration System*

Room Conditions: t = 80 F; p = 14.696 psia; W = 0.01097 lb water/lb d.a.
Temperature of Mixture Entering Expander = 100 F
Pressure of Mixture Entering Room = 14.696 psia

Temperature of Mixture Entering Room (°F)	Coefficient of Performance and Horsepower per Ton of Refrigeration for Compression and Expansion Efficiencies of:									
	100%		95%		90%		85%		80%	
	c.p.	Hp/ton	c.p.	Hp/ton	c.p.	Hp/ton	c.p.	Hp/ton	c.p.	Hp/ton
Specific humidity of mixture entering compressor = 0.01097 lb water/lb d.a.										
50	8.252	0.572	3.364	1.402	1.974	2.390	1.353	3.486	0.936	5.040
52	8.981	0.525	3.413	1.382	1.972	2.392	1.299	3.630	0.925	5.100
54	9.529	0.495	3.391	1.391	1.928	2.447	1.273	3.705	0.908	5.195
56	10.491	0.450	3.390	1.391	1.887	2.500	1.241	3.801	0.877	5.379
58	11.531	0.409	3.346	1.410	1.825	2.585	1.199	3.934	0.827	5.704
60	13.209	0.357	3.229	1.461	1.707	2.763	1.094	4.312	0.762	6.190
Specific humidity of mixture entering compressor = 0.01148 lb water/lb d.a.										
50	7.257	0.650	3.147	1.499	1.875	2.516	1.239	3.807	0.888	5.312
52	7.658	0.616	3.134	1.505	1.820	2.592	1.226	3.848	0.874	5.397
54	8.224	0.574	3.098	1.523	1.801	2.619	1.199	3.934	0.859	5.491
56	8.525	0.553	3.101	1.521	1.752	2.692	1.156	4.080	0.825	5.718
58	9.618	0.490	3.047	1.548	1.669	2.826	1.097	4.300	0.778	6.063
60	10.475	0.450	2.862	1.648	1.569	3.006	1.000	4.717	0.705	6.691

*Values extracted from Tables 18 through 22 in Appendix E.

For efficiencies of compression and expansion of 90, 85, and 80 per cent, as the temperature of the mixture entering the room increases, the coefficient of performance decreases. For an efficiency of compression and expansion of 95 per cent, as the temperature of the mixture entering the room increases, the coefficient of performance does not follow any pattern. After investigating efficiencies around 95 per cent, it was found that the differences between the coefficients of performance at different temperatures diminish. There exists an efficiency, around 95 per cent, where all of the coefficients of performance are identical, no matter what the temperature of the mixture entering the room is. It was impossible to pin-point this efficiency over the range of temperatures investigated because of the accuracy required in reading Figure 2. It would be possible to find this exact efficiency for small temperature differences, as observed in Table 1 for temperatures entering the room of 54 F and 56 F, where the coefficients of performance at 95 per cent efficiency differ by a small amount.

Specific Humidity.--Reference is made to Table 1. It is observed that for a given temperature of the mixture entering the room the coefficient of performance for a cycle employing all room air, having a specific humidity of 0.01097 lb water/lb dry air, is larger than the coefficient of performance for a cycle employing a mixture of room air and outside air having a specific humidity of 0.01148 lb water/lb dry air. When a mixture of room air and outside air is used, heat is added to the system by the mixing of the hot outside air at 95 F with the cooler room air at 80 F. This heat addition increases the temperature of the mixture entering the compressor to 82 F. This heat of mixing is heat that must be removed in the cooler in addition to the amount of heat removed to give the required amount of refrigeration. Increasing the heat rejected in the cooler while the refrigeration remains the same increases the net work of the cycle because the net work is equal to the difference between the heat rejected and the heat absorbed (refrigeration). Increasing the net work for the same amount of refrigeration decreases the coefficient of performance.

Temperature of Mixture Entering Expander.--Reference is made to Table 18 in Appendix E. As the temperature of the mixture entering the expander is decreased, the coefficient of performance increases. If the cooling water were available at temperatures below the assumed value of 85 F and/or if a counterflow heat exchanger of considerable length were employed as the cooler, it would be possible to lower the temperature of the mixture entering the expander. The pressure to which the mixture must be compressed is decreased as the temperature of the mixture entering the expander is decreased for the same amount of refrigeration. Decreasing the discharge pressure of the compressor decreases the compressor work and decreasing the temperature of the mixture entering the expander decreases the work of the expander. Decreasing the net work increases the coefficient of performance for the same amount of refrigeration.

Back Pressure of Expander.--Reference is made to Table 18 in Appendix E. It is observed that the coefficient of performance decreases as the back pressure of the expander (p_4) increases. As the back pressure is increased, the work of the expander is decreased while the work of the compressor and the refrigeration remain the same. This increases the net work, which decreases the coefficient of performance.

Two-Stage Compression.--Reference is made to Table 23 in Appendix E. It is observed that by employing two-stage compression the coefficient of performance increases for the same amount of refrigeration. When two-stage isentropic compression is used the sum of the heat rejected in the intercooler and cooler is less than the heat rejected in one cooler in one-stage compression. Decreasing the heat rejected while the refrigeration remains the same decreases the net work, which increases the coefficient of performance.

Comparison with Vapor-Compression.--In making a comparison between the vapor-compression refrigeration system and the air-cycle refrigeration system many factors would have to be taken into consideration. A brief comparison of coefficients of performance is all that is intended to be made in this analysis.

The theoretical coefficients of performance of the air-cycle refrigeration system (coefficients of performance obtained from cycles assuming isentropic compression and expansion, together with the assumptions in Chapter II) compare very favorably with the average coefficient of performance of the vapor-compression refrigeration systems (those employing Freon, Carrene, and Dielene as refrigerants). The average coefficient of performance of these refrigerants in a standard cycle

(86 F condenser and 5 F evaporator temperatures) is 4.75 and the average horsepower per ton of refrigeration is 1.00 (16). The values of the theoretical coefficient of performance and theoretical horsepower per ton of refrigeration are better than the average values of vapor-compression systems. Inefficiency of compression and expansion lowers the actual coefficients of performance of the air-cycle refrigeration system (coefficients of performance obtained from cycles assuming efficiencies of compression and expansion less than 100 per cent, together with the assumptions in Chapter II) below the average value of the coefficient of performance of the vapor-compression system. Even with an efficiency of compression and expansion of 95 per cent the largest value of the coefficient of performance in Table 1 is lower than the average value of the coefficient of performance of the vapor-compression system.

CHAPTER V

CONCLUSIONS AND RECOMMENDATIONS

Conclusions.--From this analysis it is concluded that air-cycle refrigeration, from a thermodynamic viewpoint, cannot compete with vapor-compression refrigeration unless a compressor and expander of 100 per cent efficiency are available. If such a compressor and expander were made available then the air-cycle refrigeration system becomes competitive with the vapor-compression system. In line with this conclusion, if the temperature of the mixture entering the conditioned area is going to vary, better coefficients of performance are obtained if the compression and expansion efficiencies are equal to or greater than the value of efficiency which gives equal coefficients of performance for changes in temperature of the mixture entering the room, which is approximately 95 per cent.

Various methods of increasing the coefficient of performance, such as two-stage compression and lowering the temperature of the mixture entering the expander, can be employed, but even with these methods the actual coefficient of performance is lower than the average coefficient of performance of vapor-compression cycles, unless a compressor and expander of 100 per cent efficiency are available.

By increasing the back pressure of the expander to overcome the pressure drop due to friction in the distribution system, the necessity for employing fans to overcome this pressure drop can be eliminated.

Whether the decrease in coefficient of performance is justified by the elimination of the fans is beyond the scope of this analysis.

Recommendations.--If further analysis is made of an air-cycle refrigeration system it is recommended that this analysis be made as an actual operating analysis, which would include initial and operating costs. Similar values for a vapor-compression system could be obtained and an operating comparison could be made between the two systems. Air-cycle refrigeration has proven to be better suited to aircraft air-conditioning and quite possibly, with continued development and further experience, air-cycle refrigeration systems may be used exonomically for other applications (17 and 18).

APPENDICES

APPENDIX A

ABBREVIATIONS AND SYMBOLS

Abbreviations

c.p.	coefficient of performance
d.a.	dry air
F	degrees Fahrenheit or Fahrenheit
hp/ton	horsepower required per ton of refrigeration

Symbols

c_p	specific heat at constant pressure
h	enthalpy per unit mass, Btu/lb
J	proportionality factor, 778.26 ft-lb/Btu
M	molecular weight
p	absolute pressure, lb per sq in. abs
R	perfect gas constant
s	entropy per unit mass
t	dry bulb temperature, deg F
T	absolute temperature
W	specific humidity, lb water/lb dry air
η	efficiency

Subscripts

a	dry air
c	compressor
e	expander
g	saturated state of vapor
m	mixture
s	water vapor
1	state of mixture entering compressor, theoretical and actual cycles

2	state of mixture entering cooler, theoretical cycle
2'	state of mixture entering cooler, actual cycle
3	state of mixture entering expander, theoretical cycle
3'	state of mixture entering expander, actual cycle
4	state of mixture entering room, theoretical and actual cycles
5	room conditions
6	state of mixture entering cooler if isentropic compression is assumed for the actual cycle
7	state of mixture entering room if isentropic expansion is assumed for the actual cycle

APPENDIX B

METHODS OF CALCULATION

Partial Pressure and Specific Humidity.--The partial pressure of the water vapor (p_s) in the mixture can be calculated from the following equation:

$$W = \frac{M_s p_s}{M_a p_a} \quad \text{lb water/lb dry air} \tag{1}$$

By the Gibbs-Dalton Law the pressure of the mixture equals the sum of the partial pressures of the water vapor and the dry air. Making this substitution for the partial pressure of the dry air (p_a), substituting the values for the molecular weights of water vapor and dry air (M_s and M_a) given by J. Keenan (19), and rearranging of Equation 1 yields the following equation for determining the partial pressure of the water vapor with the pressure and specific humidity of the mixture known:

$$p_s = \frac{W\, p_m}{0.622 + W} \quad \text{psia} \tag{2}$$

For the cases investigated where the mixture is saturated, the partial pressure of the water vapor equals the saturation pressure of the water vapor. The saturation pressure is obtained from the Steam Tables (20), at the dry bulb temperature of the mixture. Equation 2 is solved for the specific humidity of a saturated mixture with the pressure of the mixture and the partial pressure of the water vapor known.

Enthalpy and Entropy of Mixture.--The enthalpy of the dry air (h_a) is obtained from the Gas Tables (21) at the dry bulb temperature of the mixture. The enthalpy of the water vapor is obtained from the Steam Tables

(22) for saturated vapor (h_g) at the dry bulb temperature of the mixture and with the specific humidity known, the enthalpy due to this amount of water vapor is calculated. By the Gibbs-Dalton Law the enthalpy of the mixture is the sum of the enthalpies of the dry air and water vapor:

$$h_m = h_a + W\, h_g \quad \text{Btu/lb dry air} \tag{3}$$

The entropy of dry air (s_a) is obtained from the relation (23):

$$s_a = \Phi_a - R_a \ln \frac{p_a}{14.696} \quad \text{Btu/lb dry air deg F abs} \tag{4}$$

where:

$$\Phi_a = \int_0^T \frac{c_p}{T}\, dT \quad \text{Btu/lb dry air deg F abs} \tag{5}$$

The value of Φ_a is obtained from the Gas Tables (24) at the dry bulb temperature of the mixture.

The entropy of the water vapor (s_s) is obtained from the relation (25):

$$s_s = s_g + \frac{R_s}{J} \ln \frac{p_g}{p_s} \quad \text{Btu/lb water vapor deg F} \tag{6}$$

The saturation pressure of the water vapor (p_g) and the entropy of saturated vapor (s_g) are obtained from the Steam Tables (26) at the dry bulb temperature of the mixture. Other symbols are as defined previously.

With the specific humidity of the mixture known, the entropy due to this amount of water vapor is calculated. By the Gibbs-Dalton Law the entropy of the mixture is the sum of the entropies of the dry air and water vapor:

$$s_m = s_a + W\, s_s \quad \text{Btu/lb dry air deg F abs} \tag{7}$$

The values of the gas constants for dry air and water vapor (R_a and R_s) are given by J. Keenan (27).

Actual Work of Compression and Expansion.--The relationship between the actual and theoretical work of compression is:

$$\eta_c = \frac{h_6 - h_1}{h_2' - h_1} \times 100 \text{ per cent} \tag{8}$$

The relationship between the actual and theoretical work of expansion is:

$$\eta_e = \frac{h_3' - h_4}{h_3 - h_7} \times 100 \text{ per cent} \tag{9}$$

States 3 and 3' are on the same isothermal line and by the previous assumption that the enthalpy is a function of temperature only, h_3 is equal to h_3'. The numerical subscripts refer to the state of the mixture in the cycle, as illustrated in Figures 1, 3, and 4.

Coefficient of Performance.--"The coefficient of performance of a refrigeration machine is analogous to the efficiency of a heat engine. It is defined as the ratio of the heat received by the machine from the body that is being cooled to the net work received." (28) The heat received by the machine is the refrigerating effect and the net work received is the difference between the work of compression and expansion. The coefficient of performance for isentropic compression and expansion is:

$$\text{c.p.} = \frac{h_5 - h_4}{(h_2 - h_1) - (h_3 - h_4)} \tag{10}$$

The coefficient of performance for the actual cycle is:

$$\text{c.p.} = \frac{h_5 - h_4}{(h_2' - h_1) - (h_3' - h_4)} \tag{11}$$

Horsepower per Ton of Refrigeration.--The horsepower required per ton of refrigeration is given by R. Jordan and G. Priester (29) as:

$$\text{Horsepower per ton} = \frac{4.717}{\text{c.p.}} \tag{12}$$

APPENDIX C

ENTROPY OF A MIXTURE OF DRY AIR AND WATER VAPOR

Table 2. Entropy of a Mixture of Dry Air and Water Vapor at a Pressure of 14.696 psia

Dry Bulb Temperature of Mixture (deg F)	Specific Humidity of Mixture (lb water/lb d.a.)	Entropy (Btu/lb d.a. deg F abs)		
		Dry Air	Water Vapor	Mixture
60	0.01097	0.59291	0.02299	0.61590
65		0.59521	0.02303	0.61824
70		0.59748	0.02308	0.62056
75		0.59973	0.02312	0.62285
80		0.60196	0.02317	0.62513
85		0.60417	0.02321	0.62738
90		0.60636	0.02325	0.62961
95		0.60854	0.02330	0.63184
100		0.61068	0.02334	0.63402
105		0.61282	0.02338	0.63620
110		0.61494	0.02342	0.63836
115		0.61704	0.02346	0.64050
62	0.01148	0.59392	0.02402	0.61794
65		0.59530	0.02405	0.61935
70		0.59757	0.02409	0.62166
75		0.59982	0.02414	0.62396
80		0.60205	0.02419	0.62624
85		0.60426	0.02423	0.62849
90		0.60645	0.02428	0.63073
95		0.60863	0.02432	0.63295
100		0.61077	0.02437	0.63514
105		0.61291	0.02441	0.63732
110		0.61503	0.02446	0.63949
115		0.61713	0.02450	0.64163

Table 3. Entropy of a Mixture of Dry Air and Water Vapor at a Pressure of 15 psia

Dry Bulb Temperature of Mixture (deg F)	Specific Humidity of Mixture (lb water/lb d.a.)	Entropy Dry Air (Btu/lb d.a. deg F abs)	Entropy Water Vapor	Entropy Mixture
61	0.01097	0.59200	0.02297	0.61497
65		0.59384	0.02301	0.61685
70		0.59611	0.02305	0.61916
75		0.59836	0.02310	0.62146
80		0.60059	0.02314	0.62373
85		0.60280	0.02319	0.62599
90		0.60499	0.02323	0.62822
95		0.60717	0.02327	0.63044
100		0.60931	0.02331	0.63262
105		0.61145	0.02336	0.63481
110		0.61357	0.02340	0.63697
117		0.61649	0.02345	0.63994
62	0.01148	0.59251	0.02399	0.61650
65		0.59389	0.02402	0.61791
70		0.59616	0.02407	0.62023
75		0.59841	0.02412	0.62253
80		0.60064	0.02416	0.62480
85		0.60285	0.02421	0.62706
90		0.60504	0.02425	0.62929
95		0.60722	0.02430	0.63152
100		0.60936	0.02434	0.63370
105		0.61150	0.02439	0.63589
110		0.61362	0.02443	0.63805
115		0.61572	0.02447	0.64019

Table 4. Entropy of a Mixture of Dry Air and Water Vapor at a Pressure of 18 psia

Dry Bulb Temperature of Mixture (deg F)	Specific Humidity of Mixture (lb water/lb d.a.)	Entropy: Dry Air (Btu/lb d.a. deg F abs)	Entropy: Water Vapor (Btu/lb d.a. deg F abs)	Entropy: Mixture (Btu/lb d.a. deg F abs)
80	0.01097	0.58811	0.02292	0.61103
85		0.59032	0.02297	0.61329
90		0.59251	0.02301	0.61552
95		0.59469	0.02305	0.61774
100		0.59683	0.02310	0.61993
105		0.59897	0.02314	0.62211
110		0.60109	0.02318	0.62427
115		0.60319	0.02322	0.62641
120		0.60526	0.02326	0.62852
125		0.60732	0.02330	0.63062
130		0.60937	0.02334	0.63271
135		0.61139	0.02338	0.63477
140		0.61340	0.02341	0.63681
145		0.61540	0.02345	0.63885
150		0.61738	0.02349	0.64087
155		0.61933	0.02353	0.64286
80	0.01148	0.58817	0.02393	0.61210
85		0.59038	0.02398	0.61436
90		0.59257	0.02402	0.61659
95		0.59475	0.02407	0.61882
100		0.59689	0.02411	0.62100
105		0.59903	0.02416	0.62319
110		0.60115	0.02420	0.62535
115		0.60325	0.02424	0.62749
120		0.60532	0.02429	0.62961
125		0.60738	0.02432	0.63170
130		0.60943	0.02437	0.63380
135		0.61145	0.02441	0.63586
140		0.61346	0.02445	0.63791
145		0.61546	0.02449	0.63995
150		0.61744	0.02453	0.64197
155		0.61939	0.02457	0.64396

Table 5. Entropy of a Mixture of Dry Air and Water Vapor at a Pressure of 19 psia

Dry Bulb Temperature of Mixture (deg F)	Specific Humidity of Mixture (lb water/lb d.a.)	Entropy (Btu/lb d.a. deg F abs) Dry Air	Water Vapor	Mixture
80	0.01097	0.58440	0.02286	0.60726
85		0.58661	0.02290	0.60951
90		0.58880	0.02294	0.61174
95		0.59098	0.02299	0.61397
100		0.59312	0.02303	0.61615
105		0.59526	0.02307	0.61833
110		0.59738	0.02311	0.62049
115		0.59948	0.02316	0.62264
120		0.60155	0.02319	0.62474
125		0.60361	0.02323	0.62684
130		0.60566	0.02328	0.62894
135		0.60768	0.02331	0.63099
140		0.60969	0.02335	0.63304
145		0.61169	0.02339	0.63508
150		0.61367	0.02343	0.63710
155		0.61562	0.02346	0.63908
80	0.01148	0.58445	0.02386	0.60831
85		0.58666	0.02391	0.61057
90		0.58885	0.02395	0.61280
95		0.59103	0.02400	0.61503
100		0.59317	0.02404	0.61721
105		0.59531	0.02409	0.61940
110		0.59743	0.02413	0.62156
115		0.59953	0.02417	0.62370
120		0.60160	0.02421	0.62581
125		0.60366	0.02426	0.62792
130		0.60571	0.02430	0.63001
135		0.60773	0.02434	0.63207
140		0.60974	0.02438	0.63412
145		0.61174	0.02442	0.63616
150		0.61372	0.02446	0.63818
155		0.61567	0.02450	0.64017

Table 6. Entropy of a Mixture of Dry Air and Water Vapor at a Pressure of 20 psia

Dry Bulb Temperature of Mixture (deg F)	Specific Humidity of Mixture (lb water/lb d.a.)	Entropy Dry Air (Btu/lb d.a. deg F abs)	Entropy Water Vapor (Btu/lb d.a. deg F abs)	Entropy Mixture (Btu/lb d.a. deg F abs)
80	0.01097	0.58087	0.02279	0.60366
85		0.58308	0.02284	0.60592
90		0.58527	0.02288	0.60815
95		0.58745	0.02293	0.61038
100		0.58959	0.02297	0.61256
105		0.59173	0.02301	0.61474
110		0.59385	0.02305	0.61690
115		0.59595	0.02309	0.61904
120		0.59802	0.02313	0.62115
125		0.60008	0.02317	0.62325
130		0.60213	0.02321	0.62534
135		0.60415	0.02325	0.62740
140		0.60616	0.02329	0.62945
145		0.60816	0.02332	0.63148
150		0.61014	0.02337	0.63351
155		0.61209	0.02341	0.63550
160		0.61404	0.02344	0.63748
165		0.61636	0.02349	0.63985
80	0.01148	0.58092	0.02380	0.60472
85		0.58313	0.02384	0.60697
90		0.58532	0.02389	0.60921
95		0.58750	0.02393	0.61143
100		0.58964	0.02398	0.61362
105		0.59178	0.02402	0.61580
110		0.59390	0.02407	0.61797
115		0.59600	0.02411	0.62011
120		0.59807	0.02415	0.62222
125		0.60013	0.02420	0.62433
130		0.60218	0.02424	0.62642
135		0.60420	0.02428	0.62848
140		0.60621	0.02432	0.63053
145		0.60821	0.02435	0.63256
150		0.61019	0.02440	0.63459
155		0.61214	0.02443	0.63657
160		0.61409	0.02447	0.63856
165		0.61603	0.02451	0.64054

Table 7. Entropy of a Mixture of Dry Air and Water Vapor at a Pressure of 21 psia

Dry Bulb Temperature of Mixture (deg F)	Specific Humidity of Mixture (lb water/lb d.a.)	Entropy Dry Air (Btu/lb d.a. deg F abs)	Entropy Water Vapor	Entropy Mixture
80	0.01097	0.57752	0.02274	0.60026
85		0.57973	0.02278	0.60251
90		0.58192	0.02282	0.60474
95		0.58410	0.02287	0.60697
100		0.58624	0.02291	0.60915
105		0.58838	0.02295	0.61133
110		0.59050	0.02299	0.61349
115		0.59260	0.02303	0.61563
120		0.59467	0.02307	0.61774
125		0.59673	0.02311	0.61984
130		0.59878	0.02316	0.62194
135		0.60080	0.02319	0.62399
140		0.60281	0.02323	0.62604
145		0.60481	0.02327	0.62808
150		0.60679	0.02330	0.63009
155		0.60874	0.02334	0.63208
160		0.61069	0.02338	0.63407
165		0.61263	0.02341	0.63604
170		0.61455	0.02345	0.63800
80	0.01148	0.57757	0.02374	0.60131
85		0.57978	0.02378	0.60356
90		0.58197	0.02383	0.60580
95		0.58415	0.02387	0.60802
100		0.58629	0.02392	0.61021
105		0.58843	0.02396	0.61239
110		0.59055	0.02400	0.61455
115		0.59265	0.02405	0.61670
120		0.59472	0.02409	0.61881
125		0.59678	0.02413	0.62091
130		0.59883	0.02417	0.62300
135		0.60085	0.02421	0.62506
140		0.60286	0.02425	0.62711
145		0.60486	0.02429	0.62915
150		0.60684	0.02433	0.63117
155		0.60879	0.02437	0.63316
160		0.61072	0.02441	0.63515
165		0.61268	0.02445	0.63713
170		0.61460	0.02449	0.63909

Table 8. Entropy of a Mixture of Dry Air and Water Vapor at a Pressure of 22 psia

Dry Bulb Temperature of Mixture (deg F)	Specific Humidity of Mixture (lb water/lb d.a.)	Entropy (Btu/lb d.a. deg F abs)		
		Dry Air	Water Vapor	Mixture
80	0.01097	0.57432	0.02268	0.59700
85		0.57653	0.02272	0.59925
90		0.57872	0.02277	0.60149
95		0.58090	0.02281	0.60371
100		0.58304	0.02285	0.60589
105		0.58518	0.02289	0.60807
110		0.58730	0.02294	0.61024
115		0.58940	0.02298	0.61238
120		0.59147	0.02302	0.61449
125		0.59353	0.02306	0.61659
130		0.59558	0.02310	0.61868
135		0.59760	0.02314	0.62074
140		0.59961	0.02317	0.62278
145		0.60161	0.02322	0.62483
150		0.60359	0.02325	0.62684
155		0.60554	0.02329	0.62883
160		0.60749	0.02332	0.63081
165		0.60943	0.02336	0.63279
170		0.61135	0.02340	0.63475
175		0.61325	0.02343	0.63668
180		0.61513	0.02347	0.63860
184		0.61663	0.02350	0.64013
80	0.01148	0.57442	0.02368	0.59810
85		0.57663	0.02372	0.60035
90		0.57882	0.02376	0.60258
95		0.58100	0.02381	0.60481
100		0.58314	0.02386	0.60700
105		0.58528	0.02390	0.60918
110		0.58740	0.02394	0.61134
115		0.58950	0.02399	0.61349
120		0.59157	0.02403	0.61560
125		0.59363	0.02407	0.61770
130		0.59568	0.02412	0.61980

(continued)

Table 8. Entropy of a Mixture of Dry Air and Water Vapor at a Pressure of 22 psia (continued)

Dry Bulb Temperature of Mixture (deg F)	Specific Humidity of Mixture (lb water/lb d.a.)	Entropy		
		Dry Air	Water Vapor	Mixture
		(Btu/lb d.a. deg F abs)		
135	0.01148	0.59770	0.02416	0.62186
140		0.59971	0.02420	0.62391
145		0.60171	0.02424	0.62595
150		0.60369	0.02427	0.62796
155		0.60564	0.02432	0.62996
160		0.60759	0.02435	0.63194
165		0.60953	0.02439	0.63392
170		0.61145	0.02444	0.63589
175		0.61335	0.02446	0.63781
181		0.61561	0.02451	0.64012

Table 9. Entropy of a Mixture of Dry Air and Water Vapor at a Pressure of 23 psia

Dry Bulb Temperature of Mixture (deg F)	Specific Humidity of Mixture (lb water/lb d.a.)	Entropy Dry Air	Entropy Water Vapor	Entropy Mixture
		(Btu/lb d.a. deg F abs)		
80	0.01097	0.57131	0.02263	0.59394
85		0.57352	0.02267	0.59619
90		0.57571	0.02270	0.59841
95		0.57789	0.02276	0.60065
100		0.58003	0.02280	0.60283
105		0.58217	0.02284	0.60501
110		0.58429	0.02288	0.60717
115		0.58639	0.02292	0.60931
120		0.58846	0.02296	0.61142
125		0.59052	0.02300	0.61352
130		0.59257	0.02304	0.61561
135		0.59459	0.02308	0.61767
140		0.59660	0.02312	0.61972
145		0.59860	0.02316	0.62176
150		0.60058	0.02320	0.62378
155		0.60253	0.02324	0.62577
160		0.60448	0.02327	0.62775
165		0.60642	0.02330	0.62972
170		0.60834	0.02336	0.63170
175		0.61024	0.02338	0.63362
180		0.61212	0.02342	0.63554
185		0.61400	0.02345	0.63745
190		0.61586	0.02349	0.63935
80	0.01148	0.57136	0.02362	0.59498
85		0.57357	0.02367	0.59724
90		0.57576	0.02371	0.59947
95		0.57794	0.02376	0.60170
100		0.58008	0.02380	0.60388
105		0.58222	0.02385	0.60607
110		0.58434	0.02389	0.60823
115		0.58644	0.02393	0.61037
120		0.58851	0.02397	0.61248
125		0.59057	0.02402	0.61459

(continued)

Table 9. Entropy of a Mixture of Dry Air and Water Vapor at a Pressure of 23 psia (continued)

Dry Bulb Temperature of Mixture (deg F)	Specific Humidity of Mixture (lb water/lb d.a.)	Entropy (Btu/lb d.a. deg F abs) Dry Air	Water Vapor	Mixture
130	0.01148	0.59262	0.02406	0.61668
135		0.59464	0.02410	0.61874
140		0.59665	0.02414	0.62079
145		0.59865	0.02418	0.62283
150		0.60063	0.02422	0.62485
155		0.60258	0.02426	0.62684
160		0.60453	0.02429	0.62882
165		0.60647	0.02433	0.63080
170		0.60839	0.02437	0.63276
175		0.61029	0.02441	0.63470
180		0.61217	0.02445	0.63662
185		0.61405	0.02448	0.63853
190		0.61591	0.02452	0.64043

Table 10. Entropy of a Mixture of Dry Air and Water Vapor at a Pressure of 24 psia

Dry Bulb Temperature of Mixture (deg F)	Specific Humidity of Mixture (lb water/lb d.a.)	Entropy (Btu/lb d.a. deg F abs) Dry Air	Water Vapor	Mixture
80	0.01097	0.56839	0.02257	0.59096
85		0.57060	0.02262	0.59322
90		0.57279	0.02266	0.59545
95		0.57497	0.02271	0.59768
100		0.57711	0.02275	0.59986
105		0.57925	0.02279	0.60204
110		0.58137	0.02283	0.60420
115		0.58347	0.02287	0.60634
120		0.58554	0.02291	0.60845
125		0.58760	0.02295	0.61055
130		0.58965	0.02299	0.61264
135		0.59167	0.02303	0.61470
140		0.59368	0.02307	0.61675
145		0.59568	0.02310	0.61878
150		0.59766	0.02315	0.62081
155		0.59961	0.02318	0.62279
160		0.60156	0.02322	0.62478
165		0.60350	0.02326	0.62676
170		0.60542	0.02329	0.62871
175		0.60732	0.02333	0.63065
180		0.60920	0.02337	0.63257
185		0.61108	0.02340	0.63448
190		0.61294	0.02343	0.63637
195		0.61479	0.02347	0.63826
200		0.61663	0.02350	0.64013
80	0.01148	0.56843	0.02357	0.59200
85		0.57064	0.02361	0.59425
90		0.57283	0.02366	0.59649
95		0.57501	0.02370	0.59871
100		0.57715	0.02375	0.60090
105		0.57929	0.02379	0.60308
110		0.58141	0.02383	0.60524
115		0.58351	0.02388	0.60739

(continued)

Table 10. Entropy of a Mixture of Dry Air and Water Vapor at a Pressure of 24 psia (continued)

Dry Bulb Temperature of Mixture (deg F)	Specific Humidity of Mixture (lb water/lb d.a.)	Entropy		
		Dry Air	Water Vapor	Mixture
		(Btu/lb d.a. deg F abs)		
120	0.01148	0.58558	0.02392	0.60950
125		0.58764	0.02397	0.61161
130		0.58969	0.02400	0.61369
135		0.59171	0.02404	0.61575
140		0.59372	0.02408	0.61780
145		0.59572	0.02412	0.61984
150		0.59770	0.02416	0.62186
155		0.59965	0.02420	0.62385
160		0.60160	0.02424	0.62584
165		0.60354	0.02428	0.62782
170		0.60546	0.02432	0.62978
175		0.60736	0.02436	0.63172
180		0.60924	0.02439	0.63363
185		0.61112	0.02443	0.63555
190		0.61298	0.02446	0.63744
195		0.61483	0.02450	0.63933
200		0.61667	0.02454	0.64121

Table 11. Entropy of a Mixture of Dry Air and Water Vapor at a Pressure of 25 psia

Dry Bulb Temperature of Mixture (deg F)	Specific Humidity of Mixture (lb water/lb d.a.)	Entropy		
		Dry Air	Water Vapor	Mixture
		(Btu/lb d.a. deg F abs)		
85	0.01097	0.56780	0.02257	0.59037
90		0.56999	0.02261	0.59260
95		0.57217	0.02266	0.59483
100		0.57431	0.02270	0.59701
105		0.57645	0.02274	0.59919
110		0.57857	0.02278	0.60135
115		0.58067	0.02282	0.60349
120		0.58274	0.02286	0.60560
125		0.58480	0.02290	0.60770
130		0.58685	0.02294	0.60979
135		0.58887	0.02299	0.61186
140		0.59088	0.02302	0.61390
145		0.59288	0.02306	0.61594
150		0.59486	0.02309	0.61795
155		0.59681	0.02313	0.61994
160		0.59876	0.02317	0.62193
165		0.60070	0.02320	0.62390
170		0.60262	0.02324	0.62586
175		0.60452	0.02328	0.62780
180		0.60640	0.02331	0.62971
185		0.60828	0.02335	0.63163
190		0.61014	0.02338	0.63352
195		0.61199	0.02342	0.63541
200		0.61383	0.02345	0.63728
204		0.61527	0.02348	0.63875
210		0.61744	0.02351	0.64095
85	0.01148	0.56784	0.02356	0.59140
90		0.57003	0.02361	0.59364
95		0.57221	0.02365	0.59586
100		0.57435	0.02370	0.59805
105		0.57649	0.02374	0.60023
110		0.57861	0.02378	0.60239
115		0.58071	0.02383	0.60454

(continued)

Table 11. Entropy of a Mixture of Dry Air and Water Vapor at a Pressure of 25 psia (continued)

Dry Bulb Temperature of Mixture (deg F)	Specific Humidity of Mixture (lb water/lb d.a.)	Entropy		
		Dry Air	Water Vapor	Mixture
		(Btu/lb d.a. deg F abs)		
120	0.01148	0.58278	0.02387	0.60665
125		0.58484	0.02391	0.60875
130		0.58689	0.02395	0.61084
135		0.58891	0.02399	0.61290
140		0.59092	0.02403	0.61495
145		0.59292	0.02407	0.61699
150		0.59490	0.02411	0.61901
155		0.59685	0.02415	0.62100
160		0.59880	0.02419	0.62299
165		0.60074	0.02422	0.62496
170		0.60266	0.02427	0.62693
175		0.60456	0.02431	0.62887
180		0.60644	0.02434	0.63078
185		0.60832	0.02437	0.63269
190		0.61018	0.02441	0.63459
195		0.61203	0.02445	0.63648
200		0.61387	0.02449	0.63836
204		0.61531	0.02452	0.63983
210		0.61748	0.02456	0.64204

Table 12. Entropy of a Mixture of Dry Air and Water Vapor at a Pressure of 26 psia

Dry Bulb Temperature of Mixture (deg F)	Specific Humidity of Mixture (lb water/lb d.a.)	Entropy Dry Air (Btu/lb d.a. deg F abs)	Entropy Water Vapor	Entropy Mixture
90	0.01097	0.56729	0.02257	0.58986
95		0.56947	0.02261	0.59208
100		0.57161	0.02265	0.59426
105		0.57375	0.02269	0.59644
110		0.57587	0.02273	0.59860
115		0.57797	0.02277	0.60074
120		0.58004	0.02281	0.60285
125		0.58210	0.02286	0.60496
130		0.58415	0.02289	0.60704
135		0.58617	0.02293	0.60910
140		0.58818	0.02297	0.61115
145		0.59018	0.02301	0.61319
150		0.59216	0.02305	0.61521
155		0.59411	0.02309	0.61720
160		0.59606	0.02312	0.61918
165		0.59800	0.02316	0.62116
170		0.59992	0.02319	0.62311
175		0.60182	0.02323	0.62505
180		0.60370	0.02327	0.62697
185		0.60558	0.02330	0.62888
190		0.60744	0.02334	0.63078
195		0.60929	0.02337	0.63266
200		0.61113	0.02340	0.63453
204		0.61257	0.02343	0.63600
210		0.61474	0.02347	0.63821
90	0.01148	0.56733	0.02356	0.59089
95		0.56951	0.02360	0.59311
100		0.57165	0.02365	0.59530
105		0.57379	0.02369	0.59748
110		0.57591	0.02373	0.59964
115		0.57801	0.02378	0.60179
120		0.58008	0.02382	0.60390
125		0.58214	0.02386	0.60600

(continued)

Table 12. Entropy of a Mixture of Dry Air and Water Vapor at a Pressure of 26 psia (continued)

Dry Bulb Temperature of Mixture (deg F)	Specific Humidity of Mixture (lb water/lb d.a.)	Entropy		
		Dry Air	Water Vapor	Mixture
		(Btu/lb d.a. deg F abs)		
130	0.01148	0.58419	0.02390	0.60809
135		0.58621	0.02394	0.61015
140		0.58822	0.02399	0.61221
145		0.59022	0.02402	0.61424
150		0.59220	0.02406	0.61626
155		0.59415	0.02410	0.61825
160		0.59610	0.02414	0.62024
165		0.59804	0.02417	0.62221
170		0.59996	0.02422	0.62418
175		0.60186	0.02426	0.62612
180		0.60374	0.02429	0.62803
185		0.60562	0.02433	0.62995
190		0.60748	0.02437	0.63185
195		0.60933	0.02440	0.63373
200		0.61117	0.02444	0.63561
204		0.61261	0.02447	0.63708
210		0.61478	0.02450	0.63928

Table 13. Entropy of a Saturated Mixture of Dry Air and Water Vapor at a Pressure of 14.696 psia

Dry Bulb Temperature of Mixture (deg F)	Specific Humidity of Mixture (lb water/lb d.a.)	Entropy (Btu/lb d.a. deg F abs) Dry Air	Water Vapor	Mixture
40	0.00519	0.58289	0.01121	0.59410
42	0.00561	0.58389	0.01208	0.59597
44	0.00607	0.58489	0.01303	0.59792
45	0.00631	0.58542	0.01352	0.59894
50	0.00763	0.58791	0.01622	0.60413
52	0.00822	0.58890	0.01743	0.60633
54	0.00886	0.58993	0.01873	0.60866
55	0.00919	0.59040	0.01939	0.60979
56	0.00954	0.59091	0.02010	0.61101
58	0.01026	0.59194	0.02156	0.61350
60	0.01104	0.59295	0.02313	0.61608
62	0.01186	0.59397	0.02477	0.61874
65	0.01321	0.59549	0.02747	0.62296
68	0.01468	0.59699	0.03040	0.62739
70	0.01575	0.59800	0.03252	0.63052
73	0.01748	0.59953	0.03594	0.63547
75	0.01873	0.60059	0.03840	0.63899

Table 14. Entropy of a Saturated Mixture of Dry Air and Water Vapor at a Pressure of 15 psia

Dry Bulb Temperature of Mixture (deg F)	Specific Humidity of Mixture (lb water/lb d.a.)	Entropy (Btu/lb d.a. deg F abs)		
		Dry Air	Water Vapor	Mixture
45	0.00618	0.58403	0.01324	0.59727
50	0.00747	0.58651	0.01588	0.60239
52	0.00806	0.58750	0.01709	0.60459
54	0.00868	0.58853	0.01835	0.60688
55	0.00900	0.58900	0.01899	0.60799
56	0.00934	0.58951	0.01968	0.60919
58	0.01005	0.59054	0.02112	0.61166
60	0.01082	0.59154	0.02267	0.61421
62	0.01162	0.59256	0.02427	0.61683
65	0.01294	0.59407	0.02691	0.62098
68	0.01438	0.59558	0.02978	0.62536
70	0.01543	0.59657	0.03186	0.62843
73	0.01712	0.59812	0.03520	0.63332
76	0.01898	0.59965	0.03886	0.63851

APPENDIX D

ENTHALPY OF A MIXTURE OF DRY AIR AND WATER VAPOR

Table 15. Enthalpy of a Mixture of Dry Air and Water Vapor at Specific Humidities (W) of 0.01097 and 0.01148 lb water/lb dry air

Dry Bulb Temperature of Mixture (deg F)	Enthalpy of Dry Air (Btu/lb d.a.)	Enthalpy (Btu/lb d.a.) W = 0.01097 Water Vapor	Mixture	W = 0.01148 Water Vapor	Mixture
60	124.27	11.935	136.205	12.490	136.760
61	124.51	11.940	136.450	12.495	137.005
62	124.75	11.945	136.695	12.501	137.251
63	124.99	11.950	136.940	12.505	137.495
64	125.23	11.954	137.184	12.510	137.740
65	125.47	11.960	137.430	12.516	137.986
66	125.70	11.964	137.664	12.520	138.220
67	125.94	11.968	137.908	12.525	138.465
68	126.18	11.974	138.154	12.530	138.710
69	126.42	11.978	138.398	12.535	138.955
70	126.66	11.983	138.643	12.540	139.200
71	126.90	11.988	138.888	12.545	139.445
72	127.14	11.992	139.132	12.550	139.695
73	127.38	11.997	139.377	12.555	139.935
74	127.62	12.002	139.622	12.560	140.180
75	127.86	12.007	139.867	12.565	140.425
76	128.10	12.011	140.111	12.570	140.670
77	128.34	12.017	140.357	12.575	140.915
78	128.58	12.021	140.601	12.580	141.160
79	128.82	12.025	140.845	12.584	141.404
80	129.06	12.030	141.090	12.589	141.649
81	129.30	12.035	141.335	12.595	141.895
82	129.54	12.040	141.580	12.600	142.140
83	129.78	12.044	141.824	12.604	142.384
84	130.02	12.049	142.069	12.610	142.630
85	130.26	12.054	142.314	12.614	142.874
86	130.50	12.058	142.558	12.619	143.119
87	130.74	12.064	142.804	12.625	143.365
88	130.98	12.068	143.048	12.629	143.609
89	131.22	12.072	143.292	12.634	143.854
90	131.46	12.077	143.537	12.638	144.098
91	131.70	12.082	143.782	12.644	144.344

(continued)

Table 15. Enthalpy of a Mixture of Dry Air and Water Vapor at Specific Humidities (W) of 0.01097 and 0.01148 lb water/lb dry air (continued)

Dry Bulb Temperature of Mixture (deg F)	Enthalpy of Dry Air (Btu/lb d.a.)	Enthalpy W = 0.01097 Water Vapor	Enthalpy W = 0.01097 Mixture	Enthalpy W = 0.01148 Water Vapor	Enthalpy W = 0.01148 Mixture
		(Btu/lb d.a.)			
92	131.94	12.087	144.027	12.649	144.589
93	132.18	12.091	144.271	12.653	144.833
94	132.42	12.096	144.516	12.658	145.078
95	132.66	12.101	144.761	12.664	145.324
96	132.90	12.105	145.005	12.668	145.568
97	133.14	12.110	145.250	12.673	145.813
98	133.38	12.115	145.495	12.679	146.059
99	133.62	12.120	145.740	12.683	146.303
100	133.86	12.124	145.984	12.688	146.548
101	134.10	12.128	146.228	12.692	146.792
102	134.34	12.134	146.474	12.698	147.038
103	134.58	12.138	146.718	12.703	147.283
104	134.82	12.143	146.963	12.707	147.527
105	135.06	12.147	147.207	12.712	147.772
106	135.30	12.153	147.453	12.718	148.018
107	135.54	12.157	147.697	12.722	148.262
108	135.78	12.161	147.941	12.727	148.507
109	136.02	12.166	148.186	12.731	148.751
110	136.26	12.171	148.431	12.737	148.997
111	136.50	12.176	148.676	12.742	149.242
112	136.74	12.180	148.920	12.746	149.486
113	136.99	12.184	149.174	12.751	149.741
114	137.23	12.189	149.419	12.755	149.985
115	137.47	12.194	149.664	12.761	150.231
116	137.70	12.200	149.900	12.766	150.466
117	137.94	12.203	150.143	12.770	150.710
118	138.18	12.207	150.387	12.775	150.955
119	138.42	12.212	150.632	12.780	151.200
120	138.66	12.217	150.877	12.785	151.445
121	138.90	12.222	151.122	12.790	151.690
122	139.14	12.226	151.366	12.794	151.934

(continued)

Table 15. Enthalpy of a Mixture of Dry Air and Water Vapor at Specific Humidities (W) of 0.01097 and 0.01148 lb water/lb dry air (continued)

Dry Bulb Temperature of Mixture (deg F)	Enthalpy of Dry Air (Btu/lb d.a.)	Enthalpy W = 0.01097 Water Vapor (Btu/lb d.a.)	Enthalpy W = 0.01097 Mixture (Btu/lb d.a.)	Enthalpy W = 0.01148 Water Vapor (Btu/lb d.a.)	Enthalpy W = 0.01148 Mixture (Btu/lb d.a.)
123	139.38	12.231	151.611	12.799	152.179
124	139.62	12.235	148.855	12.804	152.424
125	139.86	12.240	152.100	12.809	152.669
126	140.10	12.245	152.345	12.814	152.914
127	140.34	12.249	152.589	12.819	153.159
128	140.58	12.254	152.834	12.823	153.403
129	140.82	12.258	153.078	12.828	153.648
130	141.06	12.263	153.323	12.834	153.894
131	141.30	12.268	153.568	12.838	154.138
132	141.54	12.272	153.812	12.843	154.383
133	141.78	12.277	154.057	12.847	154.627
134	142.02	12.281	154.301	12.852	154.872
135	142.26	12.285	154.545	12.857	155.117
136	142.50	12.290	154.790	12.861	155.361
137	142.75	12.295	155.045	12.867	155.617
138	142.99	12.300	155.290	12.871	155.861
139	143.23	12.304	155.534	12.876	156.106
140	143.47	12.308	155.778	12.881	156.351
141	143.71	12.313	156.023	12.885	156.595
142	143.95	12.317	156.267	12.890	156.840
143	144.19	12.322	156.512	12.894	157.084
144	144.43	12.326	156.756	12.899	157.329
145	144.67	12.331	157.001	12.905	157.575
146	144.91	12.336	157.246	12.909	157.819
147	145.15	12.340	157.490	12.914	158.064
148	145.39	12.345	157.735	12.918	158.308
149	145.63	12.349	156.979	12.923	158.553
150	145.88	12.353	158.233	12.928	158.808
151	146.12	12.358	158.478	12.932	159.052
152	146.36	12.362	158.722	12.937	159.297
153	146.60	12.366	158.966	12.941	159.541

(continued)

Table 15. Enthalpy of a Mixture of Dry Air and Water Vapor at Specific Humidities (W) of 0.01097 and 0.01148 lb water/lb dry air (continued)

Dry Bulb Temperature of Mixture (deg F)	Enthalpy of Dry Air (Btu/lb d.a.)	Enthalpy (Btu/lb d.a.) W = 0.01097 Water Vapor	W = 0.01097 Mixture	W = 0.01148 Water Vapor	W = 0.01148 Mixture
154	146.84	12.371	159.211	12.946	159.786
155	147.08	12.375	159.455	12.951	160.031
156	147.32	12.381	159.701	12.956	160.276
157	147.56	12.385	159.945	12.961	160.521
158	147.80	12.390	160.190	12.966	160.766
159	148.04	12.394	160.434	12.970	161.010
160	148.28	12.398	160.678	12.975	161.255
161	148.52	12.403	160.923	12.979	161.499
162	148.77	12.407	161.177	12.984	161.754
163	149.01	12.411	161.421	12.989	161.999
164	149.25	12.416	161.666	12.993	162.243
165	149.49	12.420	161.910	12.998	162.488
166	149.72	12.425	162.145	13.002	162.722
167	149.96	12.429	162.389	13.007	162.967
168	150.20	12.433	162.633	13.011	163.211
169	150.44	12.438	162.878	13.016	163.456
170	150.68	12.442	163.122	13.021	163.701
171	150.92	12.447	163.367	13.025	163.945
172	151.16	12.451	163.611	13.030	164.190
173	151.41	12.455	163.865	13.034	164.444
174	151.65	12.460	164.110	13.039	164.689
175	151.89	12.464	164.354	13.044	164.934
176	152.13	12.469	164.599	13.048	165.178
177	152.37	12.473	164.843	13.053	165.423
178	152.61	12.477	165.087	13.057	165.667
179	152.85	12.481	165.331	13.061	165.911
180	153.09	12.485	165.575	13.065	166.155
181	153.33	12.489	165.819	13.070	166.400
182	153.57	12.494	166.064	13.075	166.645
183	153.81	12.498	166.308	13.079	166.889
184	154.06	12.503	166.563	13.084	167.144

(continued)

Table 15. Enthalpy of a Mixture of Dry Air and Water Vapor at Specific Humidities (W) of 0.01097 and 0.01148 lb water/lb dry air (continued)

Dry Bulb Temperature of Mixture (deg F)	Enthalpy of Dry Air (Btu/lb d.a.)	Enthalpy			
		W = 0.01097		W = 0.01148	
		Water Vapor	Mixture	Water Vapor	Mixture
		(Btu/lb d.a.)			
185	154.30	12.507	166.807	13.088	167.388
186	154.54	12.511	167.051	13.093	167.633
187	154.78	12.516	167.296	13.098	167.878
188	155.02	12.520	167.540	13.102	168.122
189	155.26	12.524	167.784	13.107	168.367
190	155.50	12.528	168.028	13.110	168.610
191	155.74	12.532	168.272	13.115	168.855
192	155.98	12.537	168.517	13.119	169.099
193	156.22	12.541	168.761	13.124	169.344
194	156.47	12.545	169.015	13.129	169.599
195	156.71	12.550	169.260	13.133	169.843
196	156.95	12.554	169.504	13.138	170.088
197	157.19	12.557	169.747	13.141	170.331
198	157.43	12.562	169.992	13.146	170.576
199	157.67	12.566	170.236	13.150	170.820
200	157.92	12.571	170.491	13.155	171.075
202	158.40	12.578	170.978	13.163	171.563
204	158.88	12.587	171.467	13.172	172.052
206	159.36	12.596	171.956	13.181	172.541
208	159.84	12.603	172.453	13.189	173.039
210	160.33	12.612	172.942	13.199	173.529

Table 16. Enthalpy of a Saturated Mixture of Dry Air and Water Vapor at a Pressure of 14.696 psia

Dry Bulb Temperature of Mixture (deg F)	Specific Humidity of Mixture (lb water/lb d.a.)	Enthalpy Dry Air (Btu/lb d.a.)	Enthalpy Water Vapor (Btu/lb d.a.)	Enthalpy Mixture (Btu/lb d.a.)
40	0.00519	119.48	5.602	125.082
41	0.00540	119.72	5.830	125.550
42	0.00561	119.96	6.060	126.020
43	0.00584	120.20	6.311	126.511
44	0.00607	120.44	6.562	127.002
45	0.00631	120.68	6.824	127.504
46	0.00655	120.92	7.086	128.006
47	0.00681	121.16	7.371	128.531
48	0.00707	121.40	7.655	129.055
49	0.00734	121.63	7.951	129.581
50	0.00763	121.87	8.269	130.139
51	0.00792	122.11	8.586	130.696
52	0.00822	122.35	8.915	131.265
53	0.00854	122.59	9.266	131.856
54	0.00886	122.83	9.617	132.447
55	0.00919	123.07	9.979	133.049
56	0.00954	123.31	10.363	133.673
57	0.00990	123.55	10.758	134.308
58	0.01026	123.79	11.154	134.944
59	0.01065	124.03	11.583	135.613
60	0.01104	124.27	12.012	136.282
62	0.01186	124.75	12.926	137.676
65	0.01321	125.47	14.402	139.872
68	0.01468	126.18	16.023	142.203
70	0.01575	126.66	17.204	143.864
73	0.01748	127.14	19.116	146.256
75	0.01873	127.86	20.500	148.360

Table 17. Enthalpy of a Saturated Mixture of Dry Air and Water Vapor at a Pressure of 15 psia

Dry Bulb Temperature of Mixture (deg F)	Specific Humidity of Mixture (lb water/lb d.a.)	Enthalpy (Btu/lb d.a.)		
		Dry Air	Water Vapor	Mixture
45	0.00618	120.68	6.684	127.364
50	0.00747	121.87	8.095	129.965
52	0.00806	122.35	8.741	131.091
54	0.00868	122.83	9.421	132.251
56	0.00934	123.31	10.146	133.456
58	0.01005	123.79	10.925	134.715
60	0.01082	124.27	11.772	136.042
62	0.01162	124.75	12.665	137.415
65	0.01294	125.47	14.107	139.577
68	0.01438	126.18	15.696	141.876
70	0.01543	126.66	16.854	143.514
73	0.01712	127.14	18.722	145.862
76	0.01898	128.10	20.781	148.881

APPENDIX E

DATA ON CYCLES ANALYZED

Table 18. Cycle Data for Isentropic Compression and Expansion of a Mixture of Dry Air and Water Vapor

Room Conditions: t_5 = 80 F; p_5 = 14.696 psia; W_5 = 0.01097 lb water/lb d.a.

p_4 (psia)	t_4 (°F)	p_3 (psia)	t_3 (°F)	t_2 (°F)	p_1 (psia)	t_1 (°F)	W_1*	c.p.	Hp/ton
14.696	50	22.576	100	150.12	14.696	80	0.01097	8.252	0.572
14.696	52	21.863	100	144.60	14.696	80	0.01097	8.981	0.525
14.696	54	21.154	100	139.00	14.696	80	0.01097	9.529	0.495
14.696	56	20.455	100	133.21	14.696	80	0.01097	10.491	0.450
14.696	58	19.742	100	127.30	14.696	80	0.01097	11.531	0.409
14.696	60	19.023	100	121.14	14.696	80	0.01097	13.209	0.357
14.696	50	22.918	100	155.11	14.696	82	0.01148	7.257	0.650
14.696	52	22.214	100	149.60	14.696	82	0.01148	7.658	0.616
14.696	54	21.484	100	143.85	14.696	82	0.01148	8.224	0.574
14.696	56	20.765	100	138.10	14.696	82	0.01148	8.525	0.553
14.696	58	20.035	100	132.00	14.696	82	0.01148	9.618	0.490
14.696	60	19.321	100	125.80	14.696	82	0.01148	10.475	0.450
14.696	56	19.823	95	127.99	14.696	80	0.01097	11.341	0.416
14.696	56	19.200	90	122.61	14.696	80	0.01097	13.198	0.357
14.696	56	20.125	95	132.75	14.696	82	0.01148	9.570	0.493
14.696	56	19.492	90	127.40	14.696	82	0.01148	10.718	0.440
14.768	56	20.580	100	134.29	14.696	80	0.01097	8.147	0.579
14.768	56	20.891	100	139.20	14.696	82	0.01148	6.879	0.686

*Units of specific humidity (W) are lb water/lb dry air.

Table 19. Cycle Data for 95 Per Cent Efficiency of Compression and Expansion of a Mixture of Dry Air and Water Vapor

Room Conditions: t_5 = 80 F; p_5 = 14.696 psia; W_5 = 0.01097 lb water/lb d.a.

p_4 (psia)	t_4 (°F)	p_3' (psia	t_3' (°F)	t_2' (°F)	p_1 (psia)	t_1 (°F)	W_1*	c.p.	Hp/ton
14.696	50	23.097	100	158.00	14.696	80	0.01097	3.364	1.402
14.696	52	22.349	100	151.86	14.696	80	0.01097	3.413	1.382
14.696	54	21.588	100	145.71	14.696	80	0.01097	3.391	1.391
14.696	56	20.823	100	139.22	14.696	80	0.01097	3.390	1.391
14.696	58	20.063	100	132.63	14.696	80	0.01097	3.346	1.410
14.696	60	19.294	100	125.74	14.696	80	0.01097	3.229	1.461
14.696	50	23.449	100	163.11	14.696	82	0.01148	3.147	1.499
14.696	52	22.711	100	157.15	14.696	82	0.01148	3.134	1.505
14.696	54	21.944	100	150.92	14.696	82	0.01148	3.098	1.523
14.696	56	21.144	100	144.32	14.696	82	0.01148	3.101	1.521
14.696	58	20.389	100	137.59	14.696	82	0.01148	3.047	1.548
14.696	60	19.611	100	130.79	14.696	82	0.01148	2.862	1.648

*Units of specific humidity (W) are lb water/lb dry air.

Table 20. Cycle Data for 90 Per Cent Efficiency of Compression and Expansion of a Mixture of Dry Air and Water Vapor

Room Conditions: t_5 = 80 F; p_5 = 14.696 psia; W_5 = 0.01097 lb water/lb d.a.

p_4 (psia)	t_4 (°F)	p_3' (psia)	t_3' (°F)	t_2' (°F)	p_1 (psia)	t_1 (°F)	W_1*	c.p.	Hp/ton
14.696	50	23.692	100	167.39	14.696	80	0.01097	1.974	2.390
14.696	52	22.873	100	160.46	14.696	80	0.01097	1.972	2.392
14.696	54	22.065	100	153.58	14.696	80	0.01097	1.928	2.447
14.696	56	21.251	100	146.35	14.696	80	0.01097	1.887	2.500
14.696	58	20.433	100	138.85	14.696	80	0.01097	1.825	2.585
14.696	60	19.605	100	131.17	14.696	80	0.01097	1.707	2.763
14.696	50	24.072	100	172.79	14.696	82	0.01148	1.875	2.516
14.696	52	23.291	100	166.41	14.696	82	0.01148	1.820	2.592
14.696	54	22.450	100	159.12	14.696	82	0.01148	1.801	2.619
14.696	56	21.614	100	151.81	14.696	82	0.01148	1.752	2.692
14.696	58	20.767	100	144.40	14.696	82	0.01148	1.669	2.826
14.696	60	19.921	100	136.43	14.696	82	0.01148	1.569	3.006

*Units of specific humidity (W) are lb water/lb dry air.

Table 21. Cycle Data for 85 Per Cent Efficiency of Compression and Expansion of a Mixture of Dry Air and Water Vapor

Room Conditions: t_5 = 80 F; p_5 = 14.696 psia; W_5 = 0.01097 lb water/lb d.a.

p_4 (psia)	t_4 (°F)	p_3' (psia)	t_3' (°F)	t_2' (°F)	p_1 (psia)	t_1 (°F)	W_1*	c.p.	Hp/ton
14.696	50	24.453	100	177.76	14.696	80	0.01097	1.353	3.486
14.696	52	23.525	100	171.03	14.696	80	0.01097	1.299	3.630
14.696	54	22.639	100	162.98	14.696	80	0.01097	1.273	3.705
14.696	56	21.723	100	155.68	14.696	80	0.01097	1.241	3.801
14.696	58	21.110	100	146.05	14.696	80	0.01097	1.199	3.934
14.696	60	19.937	100	137.58	14.696	80	0.01097	1.094	4.312
14.696	50	24.883	100	185.01	14.696	82	0.01148	1.239	3.807
14.696	52	23.929	100	177.07	14.696	82	0.01148	1.226	3.848
14.696	54	23.026	100	168.97	14.696	82	0.01148	1.199	3.934
14.696	56	22.126	100	160.71	14.696	82	0.01148	1.156	4.080
14.696	58	21.200	100	152.21	14.696	82	0.01148	1.097	4.300
14.696	60	20.319	100	143.53	14.696	82	0.01148	1.000	4.717

*Units of specific humidity (W) are lb water/lb dry air.

Table 22. Cycle Data for 80 Per Cent Efficiency of Compression and Expansion of a Mixture of Dry Air and Water Vapor

Room Conditions: t_5 = 80 F; p_5 = 14.696 psia; W_5 = 0.01097 lb water/lb d.a.

p_4 (psia)	t_4 (°F)	p_3' (psia)	t_3' (°F)	t_2' (°F)	p_1 (psia)	t_1 (°F)	W_1*	c.p.	Hp/ton
14.696	50	25.258	100	192.46	14.696	80	0.01097	0.936	5.040
14.696	52	24.255	100	183.47	14.696	80	0.01097	0.925	5.100
14.696	54	23.247	100	174.10	14.696	80	0.01097	0.908	5.195
14.696	56	22.287	100	164.81	14.696	80	0.01097	0.877	5.379
14.696	58	21.325	100	155.42	14.696	80	0.01097	0.827	5.704
14.696	60	20.357	100	145.40	14.696	80	0.01097	0.762	6.190
14.969	50	25.749	100	199.22	14.696	82	0.01148	0.888	5.312
14.696	52	24.742	100	190.22	14.696	82	0.01148	0.874	5.397
14.696	54	23.692	100	180.63	14.696	82	0.01148	0.859	5.491
14.696	56	22.705	100	171.27	14.696	82	0.01148	0.825	5.718
14.696	58	21.725	100	161.59	14.696	82	0.01148	0.778	6.063
14.696	60	20.733	100	151.73	14.696	82	0.01148	0.705	6.691

*Units of specific humidity (W) are lb water/lb dry air.

Table 23. Cycle Data for Two-Stage Isentropic Compression and One-Stage Isentropic Expansion of a Mixture of Dry Air and Water Vapor

Room Conditions: t_5 = 80 F; p_5 = 14.696 psia; W_5 = 0.01097 lb water/lb d.a.

p_4 (psia)	t_4 (°F)	p_3 (psia)	t_3 (°F)	t_2 (°F)	p_1 (psia)	t_1 (°F)	W_1*	c.p.	Hp/ton	
		18.000	100	112.02	14.696	80	0.01097			1st Stage
		20.455	100	120.75	18.000	100	0.01097			2nd Stage
14.696	56							12.341	0.382	Total
		18.000	100	114.20	14.696	82	0.01148			1st Stage
		20.765	100	123.27	18.000	100	0.01148			2nd Stage
14.696	56							10.359	0.455	Total

*Units of specific humidity (W) are lb water/lb dry air.

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